Effect of Flight on the Noise from Turbulent Jets in the Generalized Acoustic Analogy

S. J. Leib

HX5, LLC

National Aeronautics and Space Administration

Glenn Research Center, Cleveland, Ohio 44135, USA

James E. Bridges

National Aeronautics and Space Administration

Glenn Research Center, Cleveland, Ohio 44135, USA

AIAA SCITECH Forum, National Harbor, MD
January 23-27, 2023

Work supported by:
NASA Advanced Air Vehicles Program, Commercial Supersonic Technology Project

INTRODUCTION

- Most fundamental work in jet noise has been done with a jet issuing from a fixed nozzle into a stationary ambient

- Impact of non-zero ambient (flight) stream on noise is significant !

  – Simulated experimentally by surrounding the jet in a larger ‘free jet’

  – Represented in noise prediction methods by including a non-zero free-stream velocity

Purpose and Scope of Work

- Extend a jet noise prediction method based on the Generalized Acoustic Analogy (Goldstein & Leib, 2008 ; Leib & Goldstein 2011), developed for the static case, to include a non-zero ambient stream

- Implement the extended formulation into an existing jet noise prediction code (GAA-JET)

- Compare predictions with experimental data from round, unheated, subsonic jets with flight stream

- Contribute to understanding the relation between simulated-flight data and flight-test data

The Acoustic Analogy

Generalized Acoustic Analogy (Goldstein & Leib, 2008 ; Leib & Goldstein 2011)

$$I_\omega(\boldsymbol{x}|\boldsymbol{y}) = (2\pi)^2 \Gamma_{\lambda j}(\boldsymbol{x}|\boldsymbol{y};\omega) \int \Gamma^*_{\kappa l}(\boldsymbol{x}|\boldsymbol{y}+\boldsymbol{\eta};\omega)\mathcal{H}_{\lambda j \kappa l}(\boldsymbol{y},\boldsymbol{\eta},\omega)d\boldsymbol{\eta}$$

Acoustic Spectrum

Propagator Functions (Green's function)

Source Spectrum

Approximations:

- Propagation
  - Locally Parallel Mean Flow
  - Slowly varying over correlation volume
- Source
  - Locally axisymmetric turbulence
  - Neglect enthalpy-flux sources for unheated jets

Formula for the acoustic spectrum in terms of:

- Scalar Green's function
- Five source spectral components

Extension to Non-Zero Flight Stream

- Basic formula for the acoustic spectrum in GAA is exact and completely general, valid for the case of a non-zero flight stream

- Original simplifications and modelling approximations were limited to the static case

- Free-stream conditions enter when:
  - Deriving explicit expressions for the propagator functions (Green's function)
  - Solving for Green's function
    - ➢ Far-field boundary condition
    - ➢ Axial wave-number
  - Evaluating the source spectral components
- Extended derivations and formulas are in the paper

Source Model

Source terms are components of the Reynolds stress auto-covariance

$$R_{ijkl}(\boldsymbol{y},\boldsymbol{\eta},\tau) = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T}\left[\rho v_i' v_j' - \overline{\rho v_i' v_j'}\right](\boldsymbol{y},t)\left[\rho v_k' v_l' - \overline{\rho v_k' v_l'}\right](\boldsymbol{y}+\boldsymbol{\eta},t+\tau)\,dt$$

Model:
Leib & Goldstein, 2011

$$R_{ijkl}(y,\eta,\tau) = \Big\{a_{0,0} - Z\left(a_{1,0} + 2a_{2,0}\tilde{l}^2 + 4a_{3,0}\tilde{l}^4\right) + Z^2\left(1+\frac{1}{X}\right)\left(a_{2,0} + 6a_{3,0}\tilde{l}^2\right) - Z^3\left(1+\frac{3}{X}\left(1+\frac{1}{X}\right)\right)a_{3,0}\Big\}e^{-X}$$

Exponential/Gaussian with algebraic tails

Frequency-Dependent Length Scales (Harper-Bourne, 2003)

$$\tilde{l}^2 = (l_1^2 + l_0^2)/l_0^2$$

$$X = \sqrt{\tilde{\eta}_1^2 + \tilde{\eta}_T^4 + \tilde{\xi}_1^2},\ \ \xi_1 = \eta_1 - U_c\tau\,,\ \ \tilde{\xi}_1 = \xi_1/l_0\ \ \tilde{\eta}_i = \eta_i/l_i\,,\ \ \ \tilde{\eta}_T = \sqrt{\tilde{\eta}_2{}^2 + \tilde{\eta}_3{}^2}.$$

$$U_c = \alpha_{ijkl}(U_{Cl} - U_\infty)$$

Numerical Methods and Implementation

- Numerical solution for Green's function:
  - RANS computed using the MentorGraphics® Flow Simulation
  - RANS solution is interpolated onto a structured grid
  - Solution in terms of azimuthal Fourier modes (Khavaran, 2019)

- Computation of Propagator Functions $\bar{\Gamma}_{ij}$ in terms of Green's function
  - Second-order central differences for mean flow and Green's function derivatives

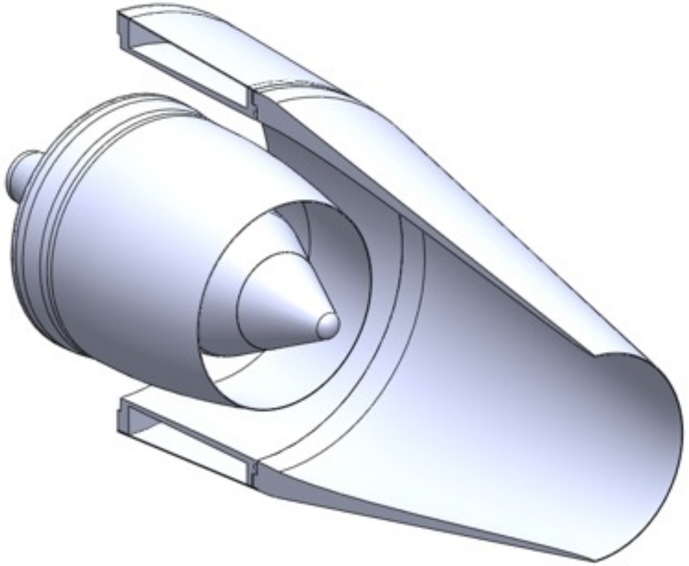
- Source model parameterized by turbulence quantities from RANS

- Integration over source volume
  - Trapezoid rule

EXPERIMENTS AND TEST CASES

- Test cases taken from experiments carried out in the Nozzle Acoustic Test Rig (NATR) at the Glenn Aero-Acoustic Propulsion Laboratory (AAPL)
- Nominally dual-stream nozzle with an internal plug and axisymmetric splitter
- Pressure- and temperature- matched streams → single-stream, unheated, axisymmetric jet
- Experimental set up, data collection, processing and free-jet shear-layer corrections in paper

Nozzle Geometry

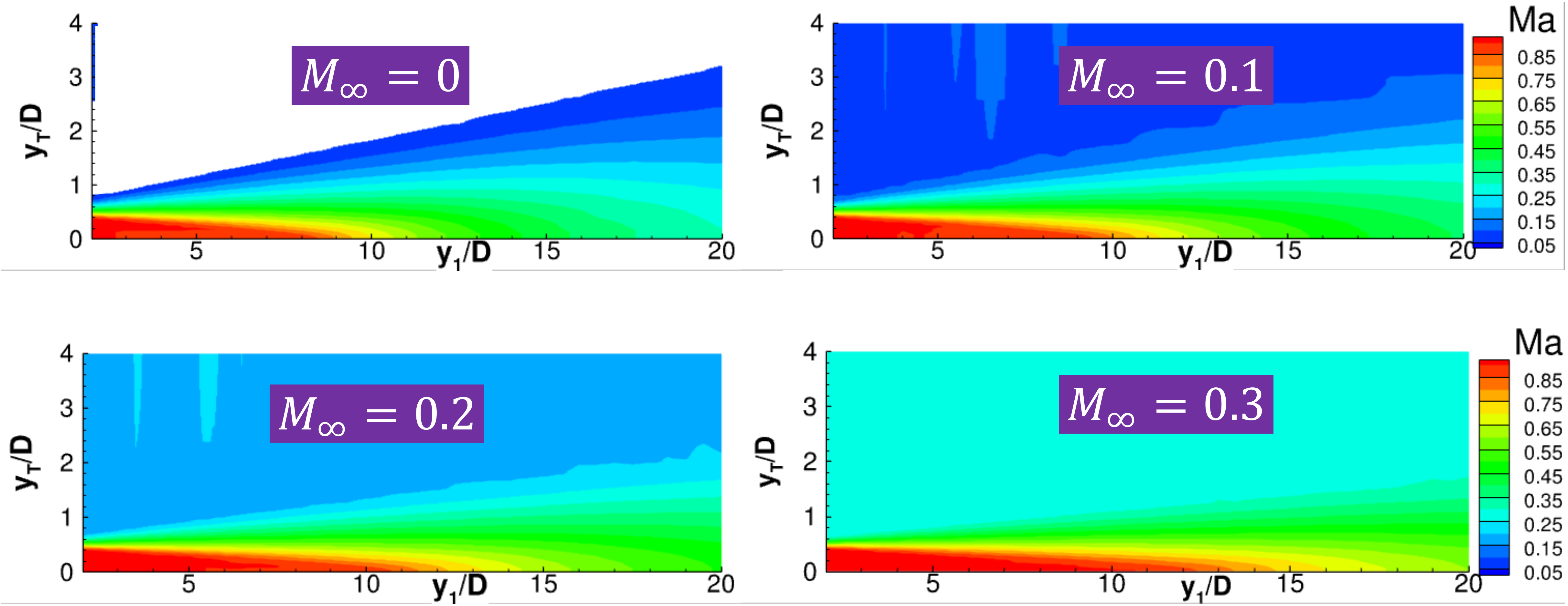


Flow Conditions

Set Point (SP)	$Ma = U_J/c_\infty$	$M_\infty = U_\infty/c_\infty$
70	0.9	0.0
71	0.9	0.1
73	0.9	0.2
75	0.9	0.3
60	0.8	0.0
61	0.8	0.1
63	0.8	0.2
65	0.8	0.3
50	0.7	0.0
51	0.7	0.1
53	0.7	0.2
40	0.6	0.0
41	0.6	0.1
43	0.6	0.2
30	0.5	0.0
32	0.5	0.1

Effect of Flight on Flow: $Ma = {}^{U}/_{c_\infty} = 0.9$

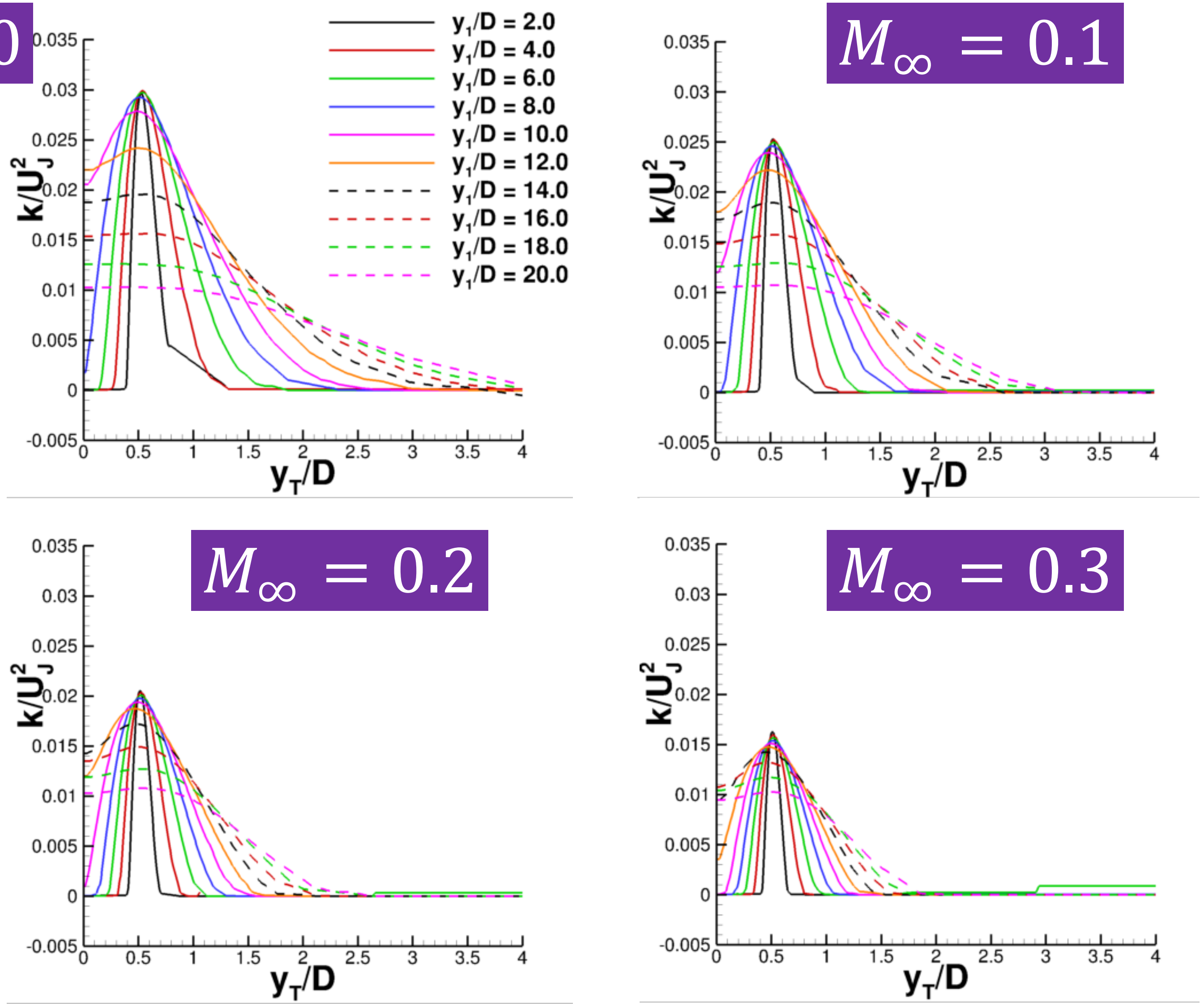
Mean Flow – Flight Stream Extends Length of Potential Core and Reduces Spreading



Effect of Flight on Turbulence: $Ma = 0.9$

Turbulence – Flight Stream Reduces Levels and Concentrates Radially

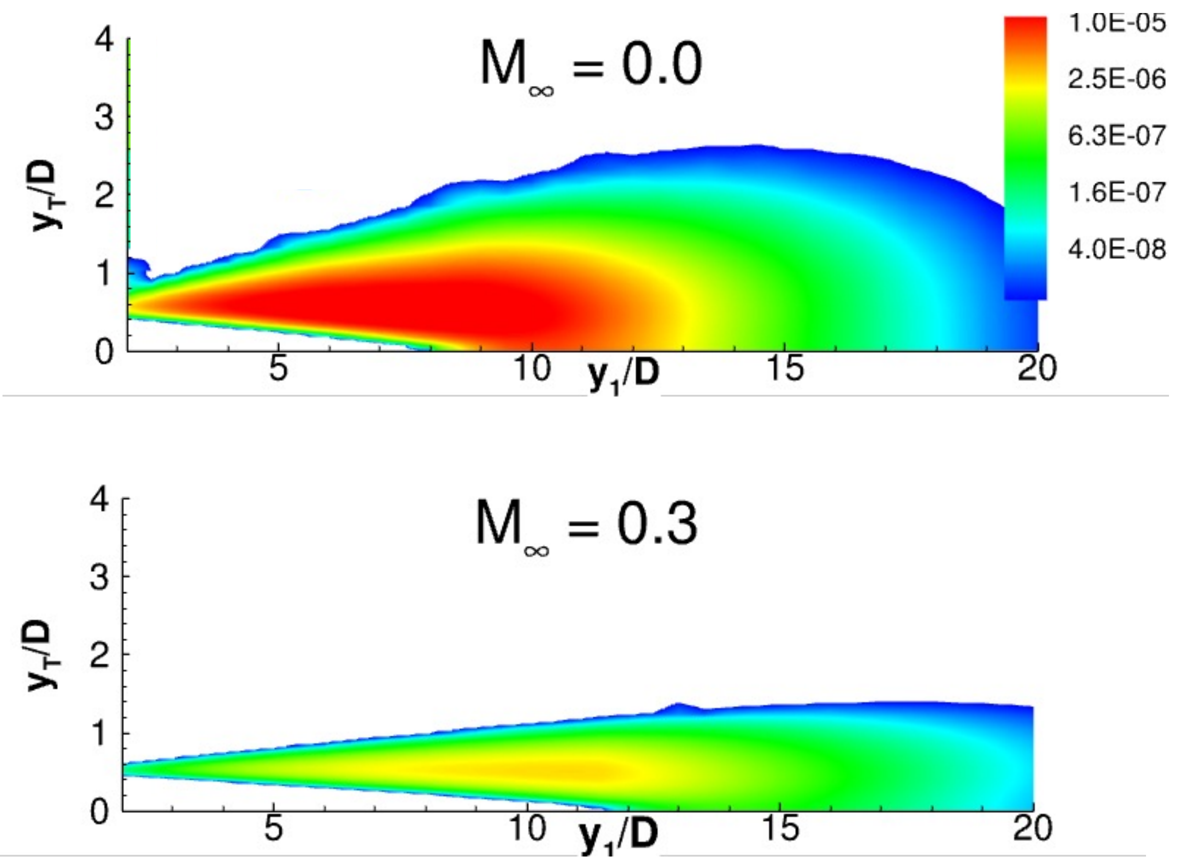
U_J= Jet Exit Velocity



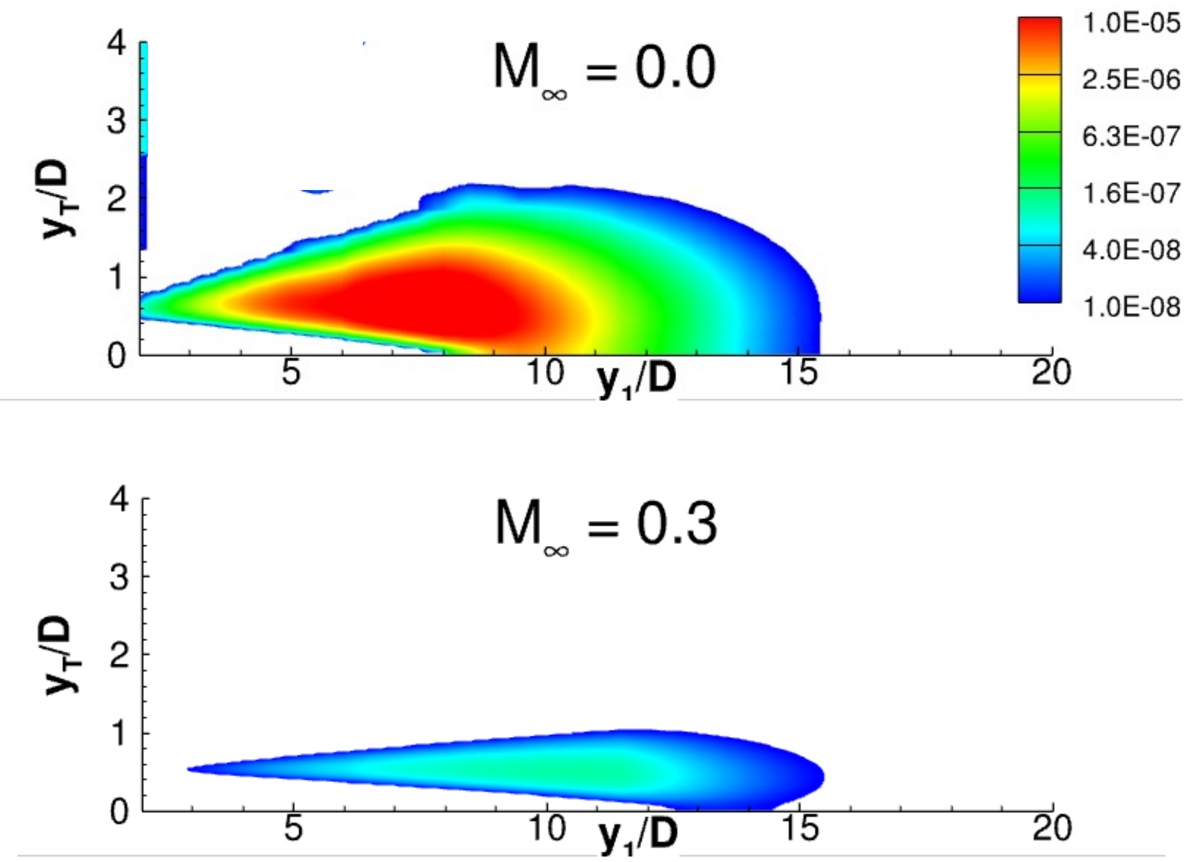
Effect of Flight on Source Distribution

$Ma = 0.9\ ; St = 0.2\ ;\ \theta = \ 30°$

Φ_{1111} - Dominates sideline



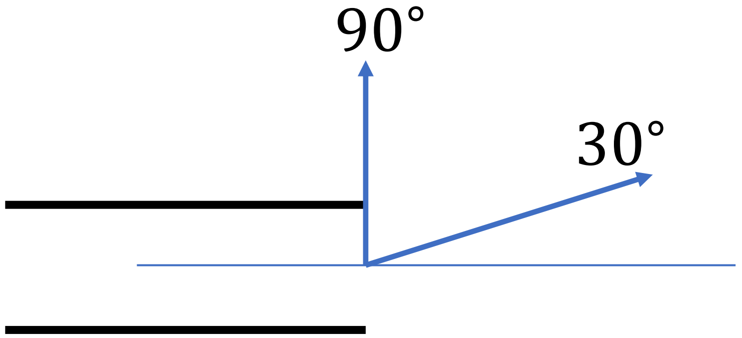
Φ_{1212} - Dominates downstream (peak)



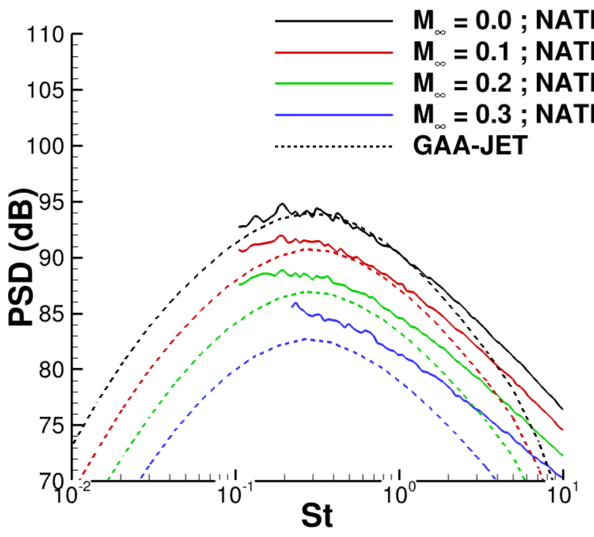
Noise Predictions – Acoustic Spectra

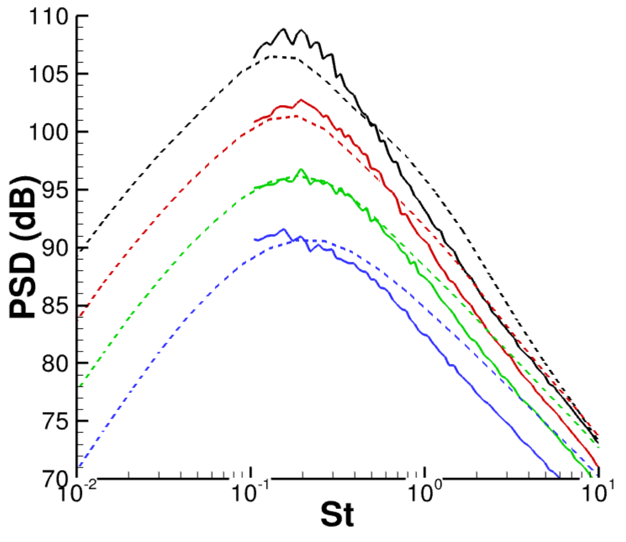
PSD per St ; Lossless
R/D = 100

$$Ma = {}^{U_J}\!/_{c_\infty} = 0.9$$



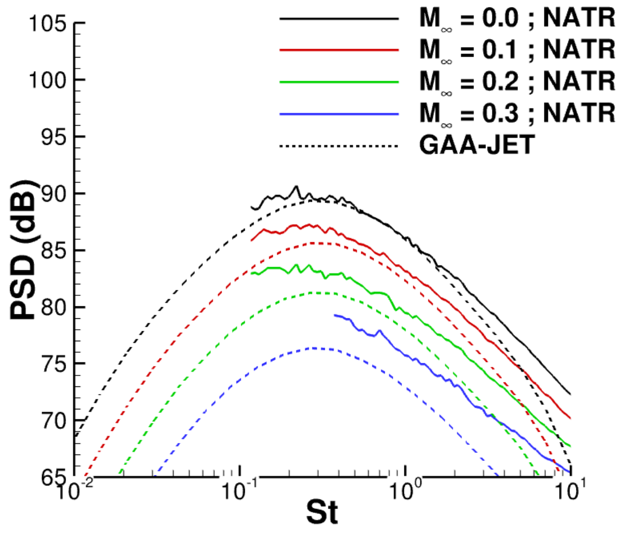
$$Ma = {}^{U_J}\!/_{c_\infty} = 0.8$$

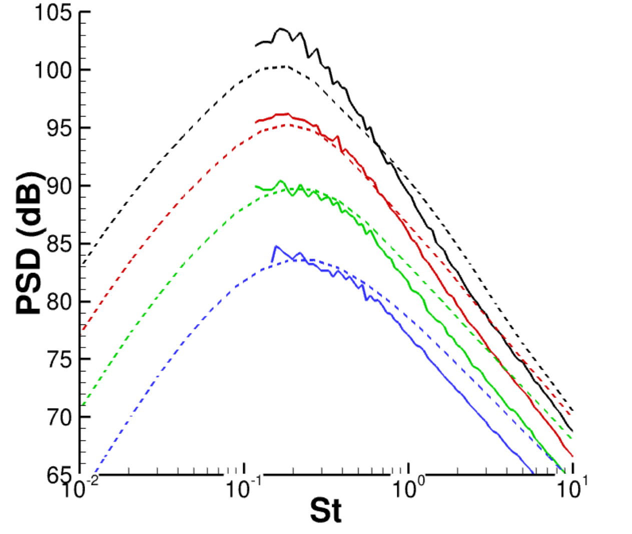




$\theta = 90°$

$\theta = 30°$

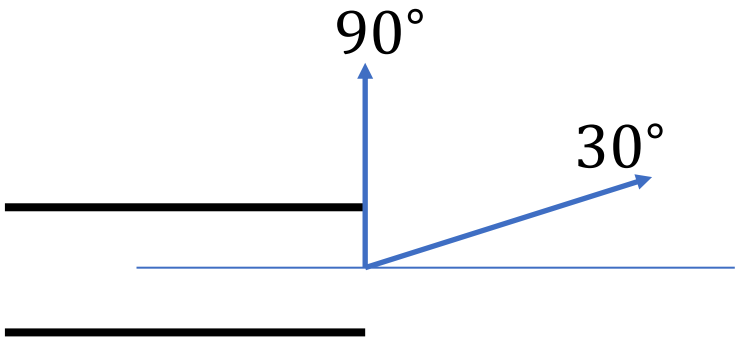




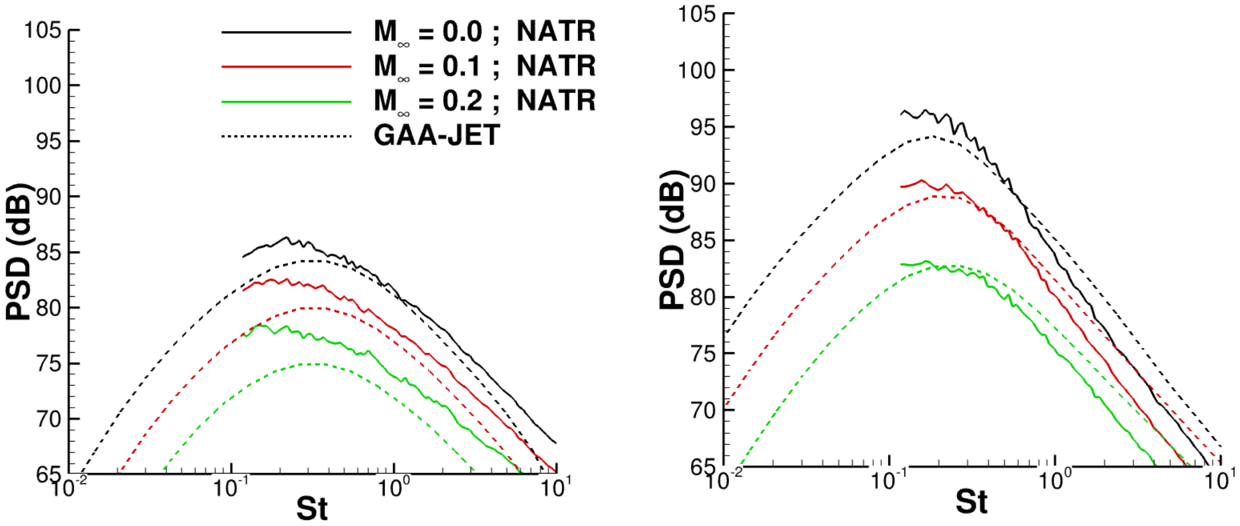
Noise Predictions – Acoustic Spectra

PSD per St ; Lossless
R/D = 100

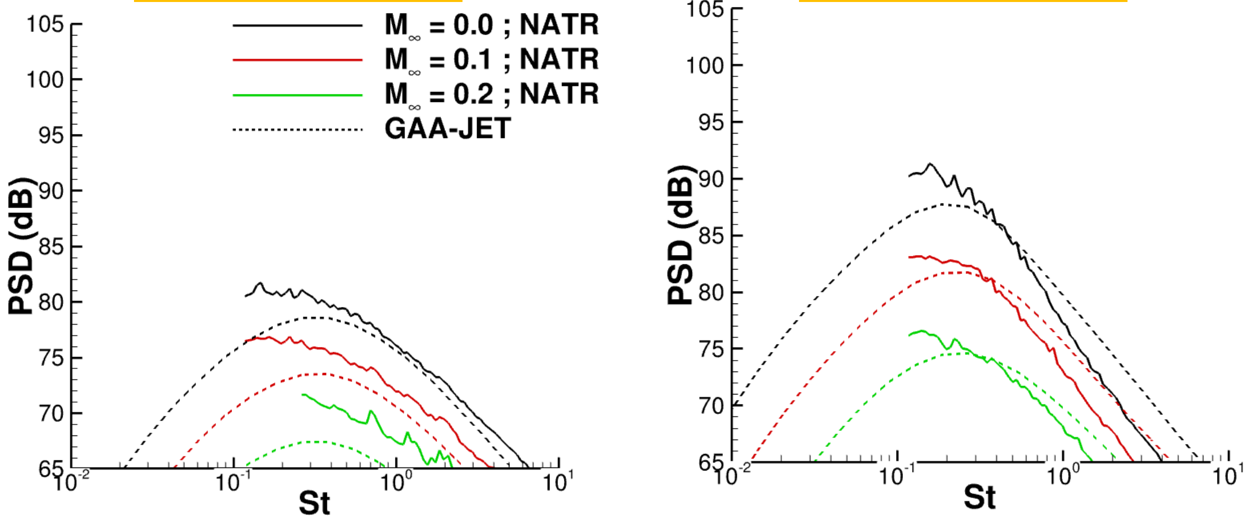
$$Ma = {}^{U_J}\!/_{c_\infty} = 0.7$$



$$Ma = {}^{U_J}\!/_{c_\infty} = 0.6$$

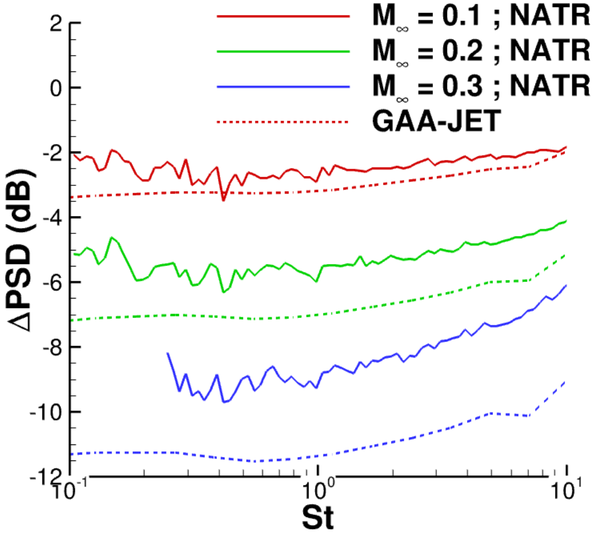


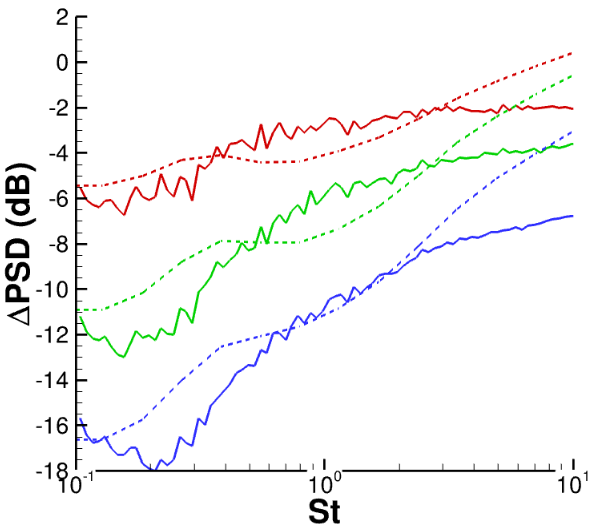
$\theta = 90°$ $\theta = 30°$



Noise Predictions – Differences from Static

$$Ma = {}^{U_J}\!/_{c_\infty} = 0.9$$

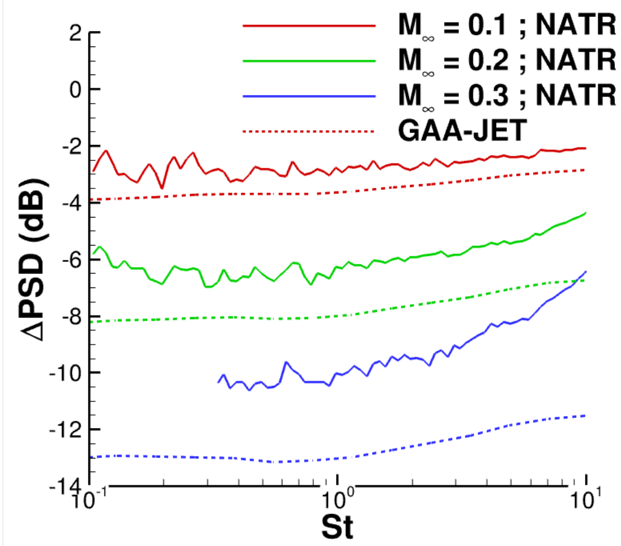


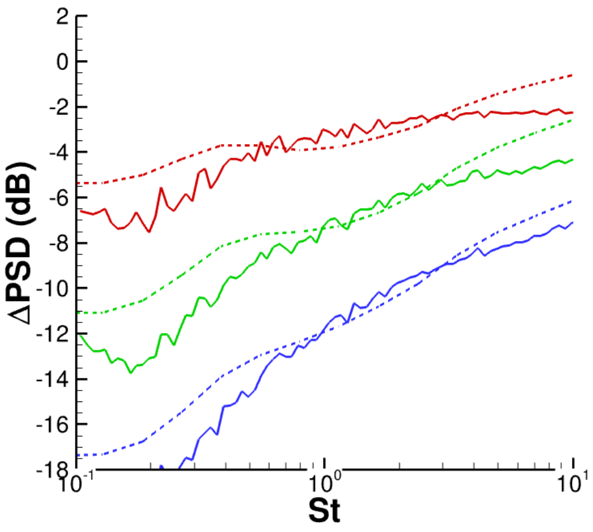


$\theta = 90°$

$\theta = 30°$

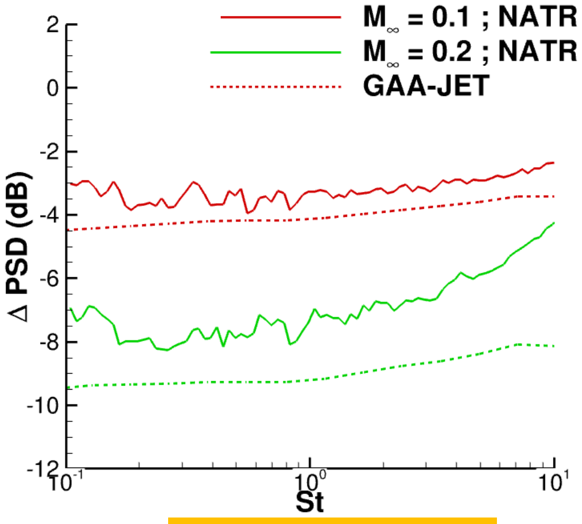
$$Ma = {}^{U_J}\!/_{c_\infty} = 0.8$$

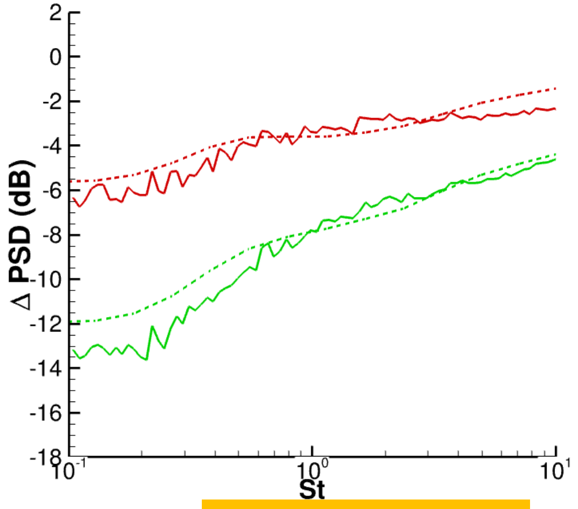




Noise Predictions – Differences from Static

$$Ma = {}^{U_J}/_{c_\infty} = 0.7$$

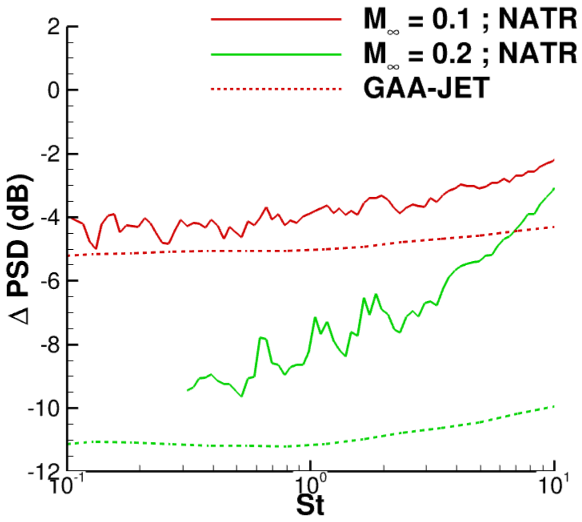


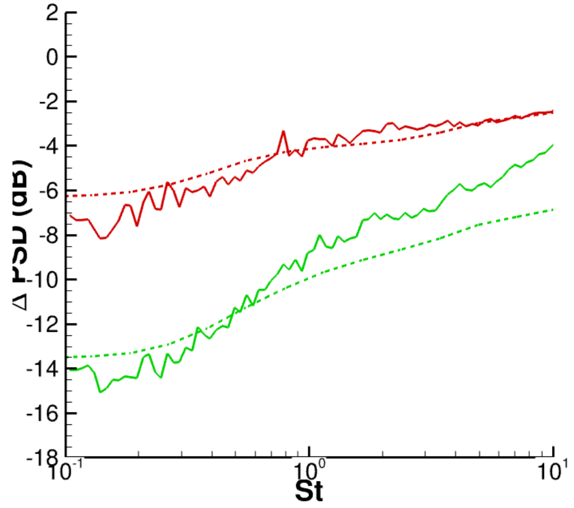


$$\theta = 90°$$

$$\theta = 30°$$

$$Ma = {}^{U_J}/_{c_\infty} = 0.6$$





Summary and Conclusions

- Extended a jet noise prediction method based on the Generalized Acoustic Analogy to include an external flight stream

- Implemented into code with existing source model developed for static jets
  – Modifications only to the turbulent convection velocity model

- Predictions capture main effect of flight stream on peak noise levels
  – Directivity and spectral characteristics captured within a few dB

- Next: More flight-appropriate source model

THE END

THANK YOU !